Advanced Technology Development For Active Acoustic Liners

NAG-1-2261

Year 1 Progress Report

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NASA-LaRC for FY00
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Overview of Year 1

Year 1 Objectives

- Develop electro-mechanical/acoustic models of a Helmholtz resonator possessing a compliant diaphragm coupled to a piezoelectric device
- Design and fabricate the energy reclamation module and active Helmholtz resonator
- Develop and build appropriate energy reclamation/storage circuit
- Develop and fabricate appropriate piezoelectric shunt circuit to tune the compliance of the active Helmholtz resonator via a variable capacitor
- Quantify energy reclamation module efficiency in a grazing-flow plane wave tube possessing known acoustic energy input
- Quantify actively tuned Helmholtz resonator performance in grazing-flow plane wave tube for a white-noise input

Year 1 Progress

- Developed electro-mechanical/acoustical models of Helmholtz resonator using lumped elements and an equivalent mass and compliance of the composite backplate
- Designed and fabricated aluminum prototype of active Helmholtz resonator with either brass/PZT or aluminum/PVDF composite backplate
- Developed and fabricated energy reclamation circuits (Kymissis /Smalser) with various electrical loads
- Developed and fabricated piezoelectric shunt circuit for tuning the active Helmholtz resonator via a variable passive network
- Demonstrated energy reclamation using active Helmholtz resonator with brass/PZT composite backplate
- Demonstrated ability to notch filter and amplify a specified frequency from a white noise acoustic input
- Demonstrated electrical tuning of notch frequencies in a grazing-flow plane wave tube
- Demonstrated ability to power a Panasonic electret microphone via the energy reclaimed by the Kymissis circuit

Theoretical Model of a Compliant-Backplate Helmholtz Resonator

An electro-mechanical/acoustical model of a Helmholtz resonator with a compliant backplate was developed. When one of the cavity walls is thin enough to flex under an applied pressure, the compliance and mass of the thin wall must be accounted for to accurately model the system. This introduces a mechanical mass and compliance across the cavity compliance of the equivalent circuit of a standard Helmholtz resonator. This changes the resonator from a 1DOF system into a 2DOF system. The equivalent circuit and schematic of the experimental setup are shown below, where R_a and M_a are the acoustic resistance and mass due to the neck, respectively, C_a is the cavity compliance, and M_m and C_m are the mechanical mass and compliance of the backplate. The symbols M_{me}' and C_{me}' represent the acoustical equivalents of their mechanical counterparts. P_1 and P_2 represent the SPL in the PWT and cavity respectively.

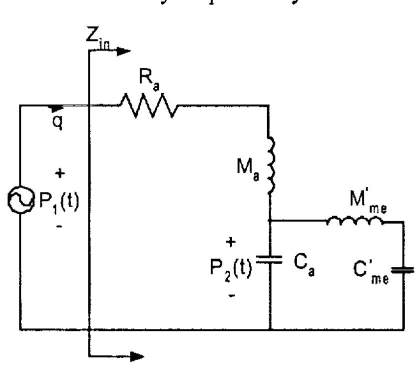


Figure 1: Acoustical equivalent circuit representation of a Helmholtz resonator with a compliant backplate.

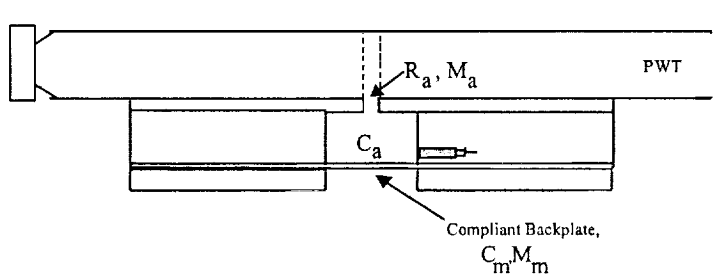


Figure 2: Schematic of PWT with flush mounted compliant-backplate Helmholtz resonator (enlarged to show detail).

Design of Prototype Active Helmholtz Resonator

A proof-of-concept prototype of the active Helmholtz resonator was designed and constructed based on the lumped element model. The prototype was constructed of modular aluminum plates. The modular design allows for the interchanging of parts to test a variety of resonator geometries. The front plate consists of a 2.34" x 10" x 0.125" aluminum plate. It contains a single 3/16" diameter, 0.125" deep hole that serves as the resonator neck for both the conventional and compliant backplate Helmholtz resonators. The middle plate, as shown below in Figure 3, contains a ½" diameter, 0.75" deep hole which serves as the resonator cavity. To mount the microphone flush against the wall of this cavity, a tapered hole was machined from the top of the plate down to the cavity, which permitted insertion of the microphone without allowing air to escape. The basic design is shown below, along with a schematic of the cavity plate used in the finished prototype.

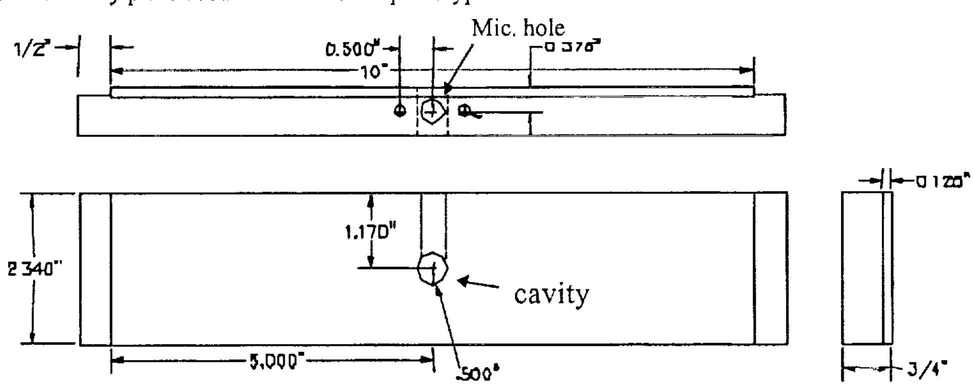


Figure 3: Schematic of the middle plate, which serves as the cavity for the prototype.

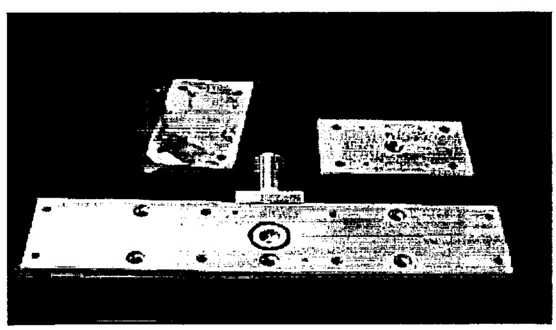


Figure 4: Photograph of prototype active Helmholtz resonator components.

Fabrication of Energy Reclamation Circuits

Two types of energy reclamation circuits, Smalser and Kymissis, were designed and fabricated, with various loads for experimentation [1,2]. A schematic of the Smalser circuit is shown in Figure 5 below. The Smalser circuit approach utilizes active impedance matching to maximize energy conversion, and consists of the following four stages:

- Stage 1: passive rectifier bridge
- Stage 2: active peak detection circuit
- Stage 3: low pass filter and active switch
- Stage 4: storage capacitor

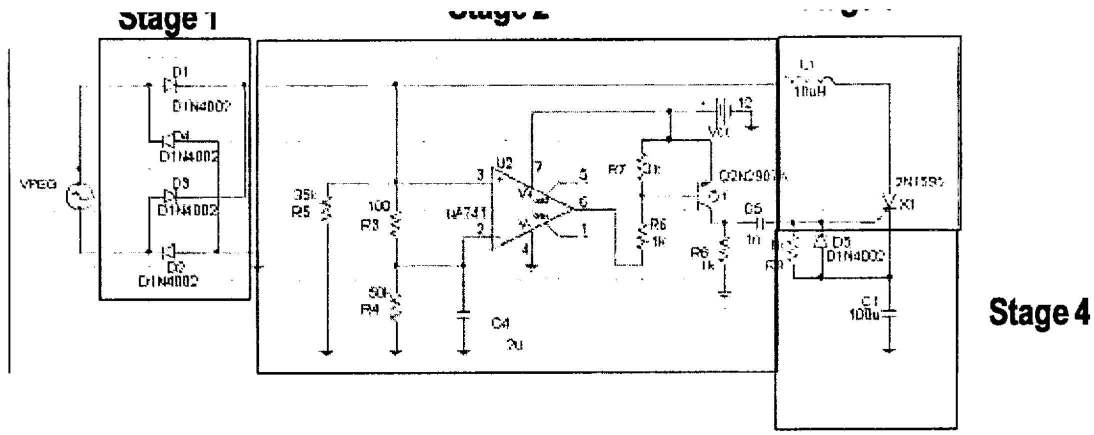


Figure 5: Schematic of Smalser circuit.

The second type of energy reclamation circuit fabricated was based on the Kymissis circuit approach. This approach utilizes passive storage elements coupled with a regulated output and also consists of four stages, which are listed below and shown explicitly in Figure 6 below.

- Stage 1: passive rectifier bridge
- Stage 2: passive storage capacitor
- Stage 3: storage capacitor 'ready' voltage detector
- Stage 4: regulator IC

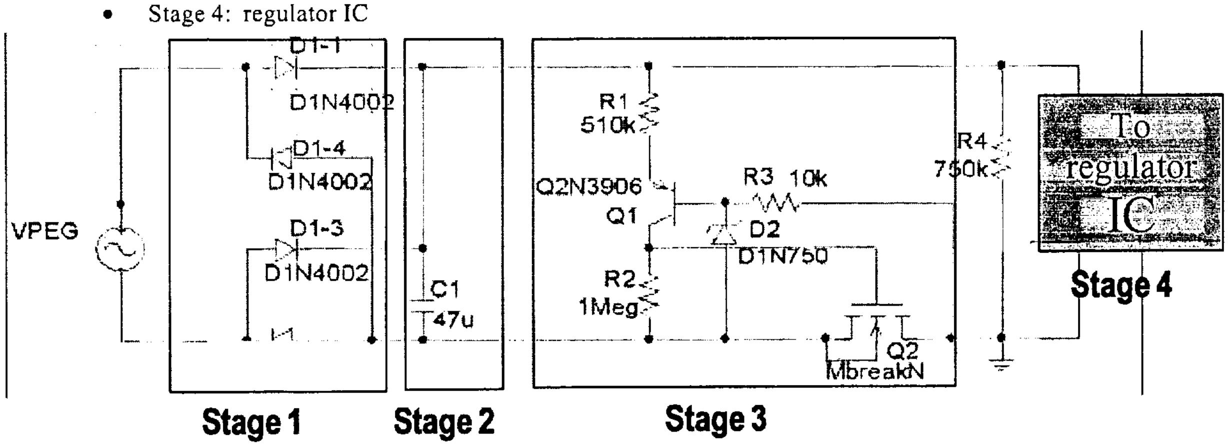
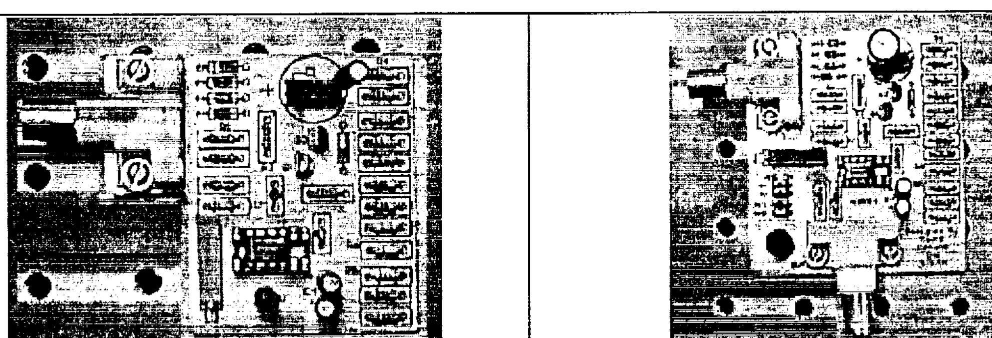


Figure 6: Schematic of Kymissis Circuit.



(A) (B)

Figure 7: (A) Kymissis circuit with Panasonic electret microphone and amplifier load (B) Kymissis circuit with LED load.

The two circuits shown in the figure above were used for verification of the energy reclamation. Both circuits are powered solely from the input signal, which was the output from the PZT in our experiments. In the case of the microphone load, a second BNC connection is used to view the output signal from the microphone that is visible in the lower left-hand side of the printed circuit board.

Experimental Results

Compliant Backplate Helmholtz Resonator

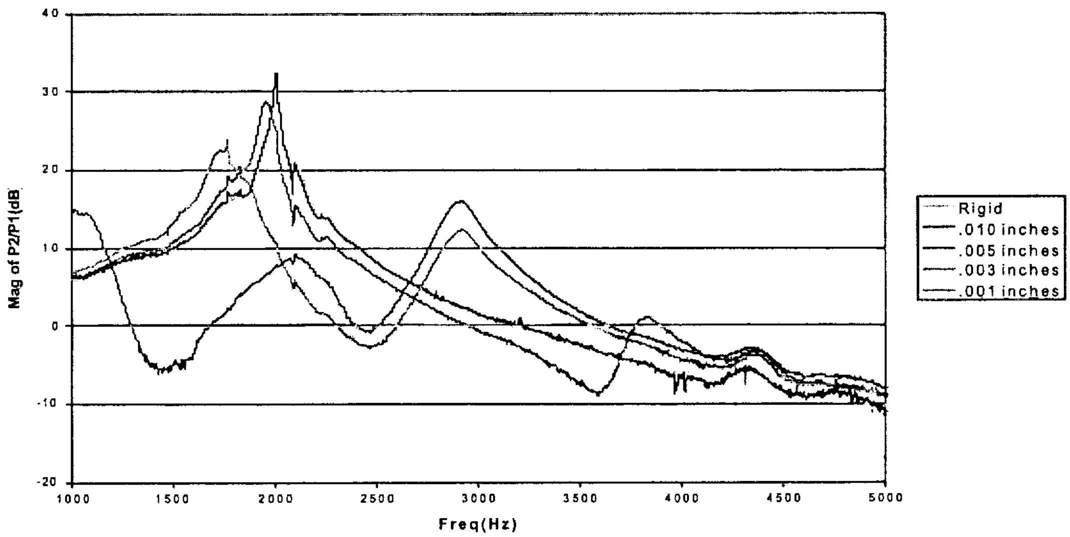


Figure 8: Resonator response vs. backplate thickness.

Experiments were performed to measure the ratio of cavity SPL to PWT SPL for various resonator backplates. The resulting transfer functions are shown in Figure 8 for backplates ranging in thickness from 0.001" to 0.25". The frequency response of a rigid backplate resonator shows a single peak at 2kHz. As the thickness of the backplate decreases, the mass goes down while the compliance increases. This causes a second resonant peak to appear at a higher frequency. The frequency of this second resonance continues to decrease as thickness decreases. When a piezoelectric element is attached to this backplate, the compliance will be varied directly through a variable capacitive network, resulting in a change in the response similar to what is shown in Figure 8.

Active Helmholtz Resonator Tuning

As a first step in developing the capacitive shunt tuner, we examined the effects of both an open- and short-circuit shunt across the piezoelectric. The experiment was performed using a PZT/brass composite backplate on the prototype resonator. The PZT/brass backplate is made from a PZT bender element supplied by American Piezo Corp. It consists of a brass disk, 7 mils thick, bonded to a thin PZT disk. The brass disk was slightly larger than 1" in diameter and was clamped at the edges by sandwiching it between two aluminum plate with 1" diameter holes. The sandwich structure was then clamped to the backside of the prototype cavity plate. The results of the open and short circuit test are shown below.

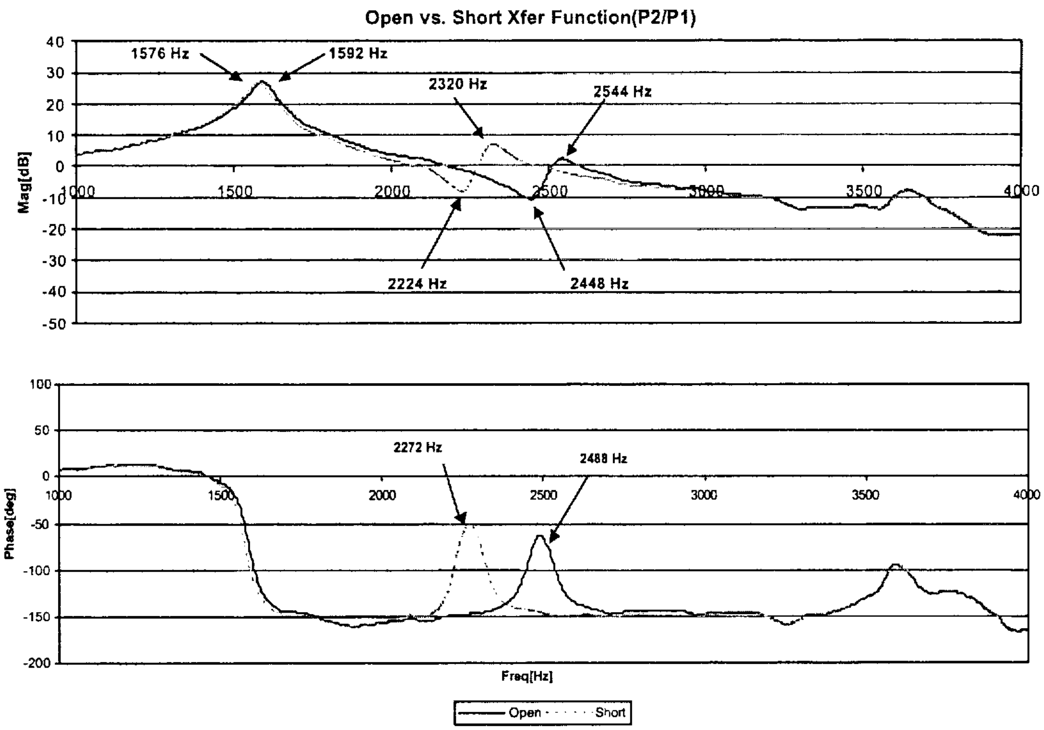


Figure 9: Frequency response for open vs. short circuit shunt across the PZT electrodes.

The first resonant peak shifts by 16 Hz, while the second resonance shifts by 224 Hz, between open and short circuit frequency responses. The open and short circuit frequency responses shown above represent the limits of tuning for this resonator geometry when using a capacitive or resistive shunt, as an open and short circuit represent the limits of impedance variations. Because of the topology of the system, a capacitive or resistive shunt across the piezoelectric does not add additional degrees of freedom to the system. An additional degree of freedom can be obtained by shunting the piezoelectric with an inductor. This will introduce an additional resonant and anti-resonant peak, which can be used to induce a shift over a larger range. Future tests will investigate this possibility. An improvement in the tuning range can be achieved through an optimization of the backplate impedance. A more accurate PZT/plate model is needed for these improvements.

Energy Reclamation

Additional tests were performed to demonstrate energy reclamation. First, the output voltage of the PZT was viewed on an oscilloscope while an acoustic signal was input to the plane wave tube. For a 120 dBSPL band-limited white noise input signal centered around the second resonant frequency used as input in the plane-wave tube, the measured PZT voltage was 106 V_{pp}. Next, the PZT output voltage was measured using an SRS SR785 spectrum analyzer. The results are shown below for a band-limited white noise acoustic source from 1kHz to 7.4kHz.

As can be seen in Figure 10, the peak voltage occurs at 2.5 kHz, which corresponds to the second resonant frequency. The actual voltage values at any one frequency are much lower than the 106 V_{pp} that was achieved when the bandwidth of the source was focused on this peak. This is due primarily to a limitation in the output power of the source that was used to generate the acoustic signals. As the bandwidth of the source is increased this power is spread over a larger area, so only low voltages were achievable when viewing output due to wide-band input signals. Despite the lower power, the wide-band noise is useful in evaluating the overall shape of the voltage spectrum

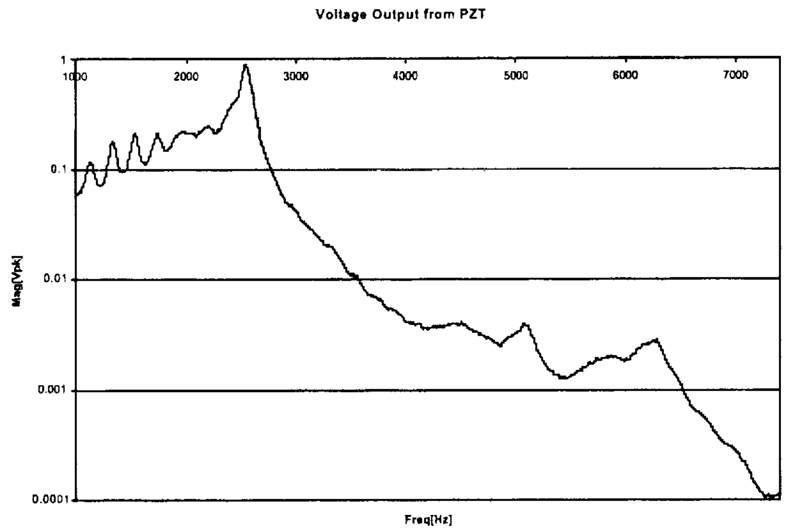


Figure 10: Voltage from PZT mounted on brass backplate for ~120dBSPL at 2500 Hz in the resonator cavity.

Additional tests were performed to determine if the voltage output was high enough to utilize the Kymissis circuit. The PZT terminals were connected to the Kymissis circuit with an LED load attached. This particular configuration of the circuit was designed to store energy from the input signal and periodically discharge this energy through an LED load to provide visual output of successful energy reclamation. When a white noise acoustic signal was input to the plane-wave tube, to which the resonator was attached, the LED periodically flashed, as the stored energy was discharged, indicating that the PZT did indeed provide enough output to drive the switching and storage circuitry of the Kymissis circuit.

As part of the overall characterization of energy reclamation efficiency, the efficiency of the Kymissis circuit was evaluated for various voltages supplied by the PZT, and was found to vary around 14%, as shown below.

V_{PZT}	P_{PZT}	Output Power	Efficiency
14 V_{rms}	1.53 mW	211.4 μW	13.8%
17 V_{rms}	2.04 mW	297.3 μW	14.6%
20 V_{rms}	2.77 mW	0.398 mW	14.3%
22 V_{rms}	3.28 mW	0.464 mW	14.1%

Future Work

Future work will focus on optimizing the liner for energy reclamation and active tuning. Additional work will be performed to characterize the absorption coefficient of the liner. For this characterization, normal impedance measurements will be performed using the in-situ and two-microphone measurement methods with the liner mounted at the end of a plane wave tube.

In order to optimize the impedance of the liner, an accurate theoretical model of the composite backplate is needed. The composite model will further allow for more precise prediction of tuning and energy reclamation capabilities of various geometries. To extend the performance of the energy reclamation module, novel switching circuits will be investigated. These should provide an improved efficiency, and wider operating range over the Kymissis and Smalser circuits that were already tested. Finally, the variable passive network will be developed further to improve the tuning capability of the active liner.

Publications/Patents:

- Horowitz, S., Nishida, T., Cattafesta, L, and Sheplak, M., "Compliant-Backplate Helmholtz Resonators for Active Noise Control Applications", AIAA Paper 2001-0817, to be presented at the 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV January 8-11, 2001.
- Disclosure: "Self-Powered, Wireless, Active Acoustic Liner," Sheplak, M., Nishida, T., and Cattafesta, L., University of Florida Office of Technology and Licensing, disclosed 1/18/00, provisional patent filed 2/28/00.

References

1. U.S. Patent 5,703,474, issued Dec. 30, 1997, "Power transfer of piezoelectric generated energy," Inventor: Paul; Smalser, Assignee: Ocean Power Technologies, West Trenton, NJ.
2. John Kymissis, Clyde Kendall, Joseph Paradiso, Neil Gershenfeld, "Parasitic Power Harvesting in Shoes", 2nd International Symposium on Wearable Computers, 19-20 October, 1998, Pittsburgh, Pennsylvania (IEEE, Piscataway, 1998), pp. 132-139.